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EXPERIMENTS IN PHYSICS

IVES

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FROM

Leslie Lyle Campbell

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AN ANNOTATED LIST OF EXPERIMENTS IN PHYSICS

SUITABLE FOR A COLLEGE COURSE

COMPILED BY

JAMES EDMUND IVES, PH.D.
ASSOCIATE PROFESSOR OF PHYSICS IN THE UNIVERSITY OF CINCINNATI

GINN AND COMPANY
BOSTON · NEW YORK · CHICAGO · LONDON

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Leslie Lyle Campbell

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PREFACE

The original edition of this book was printed in 1906 on the press of the University of Cincinnati.

It is not intended to be a course in Experimental Physics, but, as its title implies, an annotated list of some three hundred experiments, any one of which might be profitably performed by a sophomore student in college. As a rule no attempt has been made to describe the experiment, but a reference has been given to a full description of it in a standard manual or text-book.

In the references, for the sake of brevity, the name of the author has been given without the title of the work. Below, therefore, is a list of the books referred to, with their publishers:

✓Ames and Bliss, Experiments in Physics, Harper & Brothers, 1898.
✓Barker, Physics, second edition, Henry Holt & Co.
Duff, Elementary Experimental Mechanics, The Macmillan Company, 1905.
✓Ganot's Physics, translated by Atkinson, eighteenth edition, Wm. Wood & Co.
✓Glazebrook and Shaw, Practical Physics, fourth edition, Longmans, Green & Co.
✓Hastings and Beach, General Physics, Ginn and Company, 1903.
Henderson, Practical Electricity and Magnetism, new edition, Longmans, Green & Co., 1904.
Kohlrausch, Physical Measurements, third edition, D. Appleton & Co., 1899.
Mann, Advanced Optics, Scott, Foresman & Co., 1902.
✓Miller, Laboratory Physics, Ginn and Company, 1903.

MILLIKAN, Mechanics, Molecular Physics and Heat, Ginn and Company.

NICHOLS, Laboratory Manual, Volume I, Macmillan & Co., 1894.

PRESTON, Theory of Heat, second edition, Macmillan & Co., 1904.

SABINE, Laboratory Course in Physical Measurements, Ginn and Company, revised edition.

STEWART and GEE, Elementary Practical Physics, three volumes, Macmillan & Co.

STRATTON and MILLIKAN, Laboratory Experiments, University of Chicago Press, 1898.

WATSON, Practical Physics, Longmans, Green & Co., 1906.

WATSON, Textbook of Physics, fourth edition, Longmans, Green & Co.

WHITING, Physical Measurements, four volumes, John Wilson & Son.

In a few cases it has not been possible to give a reference to any of the above manuals, and therefore the manner of carrying out the experiment has been described briefly.

In the cases of Experiments 2, 3, 5, 21, 22, 117 and 118, the results of actual experiments are given in order that the student may see how they should be recorded. For Experiment 21, on the Law of the Simple Pendulum, a sample curve has been plotted.

Experience shows that each experiment will, as a rule, occupy one laboratory period of about three hours. If a student has two laboratory periods of about this length of time a week, the maximum number of experiments that he will be able to perform during the academic year will be about sixty-four. Every student ought to be able to do at least fifty during the year. These could be apportioned in the following manner: Mechanics 12, Sound 4, Heat 10, Light 12, and Electricity and Magnetism 12.

It will be necessary for the Instructor to select from these experiments, those which in his judgment can be performed to the best advantage by the student. The nature of the experiments chosen will depend upon the character and quantity of the apparatus at the command of the instructor, upon the previous experience of the student, and upon the course which the student is pursuing in college. Thus, for instance, some difference may advantageously be made in the work assigned respectively to academic and engineering students. And again there may be some difference in the assignments according as the student is pursuing physics as a major subject, or does not intend to take further work in it. Also some variation may perhaps be made for the different courses in Engineering: Mechanical, Civil, Electrical, and Chemical.

Some of the experiments can, in my opinion, be performed by the student with greater profit than others. Such experiments I have marked with a star.

Any experiment which a student has already performed creditably in a high school or preparatory school should not, of course, be repeated.

JAMES E. IVES.

CINCINNATI, Ohio.

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INSTRUCTIONS TO THE STUDENT

The student should provide himself with a note-book of the kind recommended by the Instructor. If it is made of cross-section paper, the curves can be plotted directly in it, avoiding the use of detached sheets.

The student's name and the title of the course should be written on the label on the outside of the note-book, thus:

John A. Jones
Physics 2

and also on the inside of the book. On the back of the book a small label should be pasted with the student's name, or initials, upon it, so that when standing upon a book-shelf with others it can be readily picked out.

Observations and results should be recorded on the *right-hand pages*, the *left-hand pages* being used only for making *computations*, such as addition, subtraction, multiplication, and division, either directly or by the use of logarithms.

Always begin a new page for a new experiment. The *number* of the experiment, its *title*, and the *date* on which it is made should be recorded on the top of the page, thus:

October 4th, 1911
EXPERIMENT 3
THE MICROMETER CALIPER

After the title of the experiment should come, in the following order:

(1) a statement of the object of the experiment;
(2) the general theory of the experiment;
(3) a brief description of the apparatus used;
(4) the record of observations, and
(5) a statement of the results obtained.

At the close of the experiment, the student should state what he considers to be the probable percentage error of his result. The percentage error is the fractional part of a result, expressed in percentage, that it differs from the true value. The accuracy of a result is always measured in terms of *percentage* error.

Whenever possible, observations and results should be *tabulated* as shown in Experiments 2, 3, 5, 21 and 22 in this book. Where tabulation is not possible, everything should be recorded clearly and distinctly, as shown in Experiments 117 and 118. The *displaying* of results is a very important matter. In order that the results obtained may be of the greatest service and receive proper recognition they must be well displayed. However good they may be, they will be of no value unless others besides yourself can read and understand them. To this end, the student should endeavor to write clearly and distinctly. Beauty in writing is not essential, but clearness is.

All observations, results, and computations must be recorded directly in the note-book, and no scraps of paper must be used in the laboratory for any purpose whatever. By computations are meant all multiplications, divisions, additions, and subtractions, and all operations with logarithms. It is therefore intended that everything connected with the experiment should be recorded in the note-book. Also, no observations or computations having once been made in the note-book, should be erased. If it is necessary to discard an observation or computation, simply draw lines through it. If a whole page is to be discarded, draw a line diagonally across the page and write upon the page "Discarded," and briefly state the reason. *No pages should on any account be torn out of the note-book,* as it is desired that the note-book should contain a *complete* record of the work done in the laboratory.

If another student performs an experiment with you, record his name.

Record the names of all pieces of apparatus used in an experiment.

Be careful to state the *units* used after every recorded measurement, and to state clearly in what units your final result is expressed. The units in which a quantity is measured must *always* be *stated.*

Every experiment should be completely finished, computations as well as observations, before another is commenced.

Every student is advised to provide himself with a book of logarithmic tables; that compiled by the late Professor George William Jones of Cornell University is recommended. This book contains not only tables of the logarithms of the numbers, and of the trigonometric functions, but also tables of the Naperian logarithms, of squares, cubes, square roots, cube roots, and of many other useful quantities. Logarithms should be used, wherever possible, in making calculations, as much time and labor will be saved by so doing, and the records in the note-book will be neater.

In his calculations and results the student should endeavor to use the proper number of figures, no more and no less. The figures which have a meaning are called *significant figures.* An excellent treatment of this subject is given in Sabine's "Laboratory Course in Physical Measurements," Appendix I. Students are apt to use too many figures in their results, and thus waste time in unnecessary calculations, and render their results misleading and ridiculous. For instance, a student actually recorded the weight of a body "in vacuo" as 52.515753033 grams! This is ridiculous, because with the balance used the weight could not be determined more closely than to one tenth of a milligram. He should have written his result 52.5158 grams. The additional figures, in the value that he gave, arose in making the corrections for interpolation, double weighing and buoyancy. But of course they are meaningless. We may assume that if the weighing was made carefully, all of the six figures which we have kept are known accurately with the exception of the last one, the eight. This case illustrates the general rule, which is, to *keep one uncertain figure and only one.* The six figures kept are *significant.*

An approximate rule for the product or quotient of two or more numbers, which serves for most purposes, is to keep in the product or quotient as many figures as there are in that factor which has the least number of significant figures. This rule follows from the fact that where we have a product or quotient of two or more numbers the result cannot be known more accurately than is the least accurate of the quantities involved.

It is well to remember that when a quantity is squared, its percentage error is doubled; when cubed, trebled, and so on. Also that when a quantity is found by taking the difference of two other quantities, the percentage error in the difference may be very large. The reason for this is obvious.

The student should *always* record his observations and results in *decimal,* and not in vulgar fractions.

For excellent instructions for the plotting of curves, the student is referred to Appendix II, in Sabine's "Laboratory Course in Physics." In connection with Experiment 21, on "The Law of the Simple Pendulum," a sample curve has been given, so that the student may see exactly how such a curve should be plotted. This curve shows, graphically, the relation of the *period* of a simple pendulum to its *length*. Such a curve may be used not only for the purposes of interpolation, but also to determine approximately the algebraic relation existing between the two quantities which are plotted. For this latter use, some knowledge of analytical geometry is necessary. If the note-book is made of cross-section paper, the curves can be plotted directly in it. *If the curve is plotted on a separate piece of paper, it must be pasted securely in the note-book so that it cannot be lost.*

When plotting a curve, start by ruling two co-ordinate axes at right angles to each other, one vertical on the left-hand side of the page, and one horizontal at the bottom of the page. Then take a suitable number of cross-section divisions for each unit. The vertical and horizontal scales need not be the same. Always indicate the points by means of which the curve is drawn by crosses or circles, thus, +, ×, or ⊙. Never use dots, as they are liable to be lost to sight when you draw in the curve, and it is very important to be able to see at a glance the points upon which the curve is based. Always take a separate page for a curve.

Excellent tables of physical constants will be found at the end of the various manuals referred to, especially in those of Kohlrausch, Miller, and Ames and Bliss. The Smithsonian Physical Tables published by the Smithsonian Institute will also be found useful.

Note-books, when not in use, should be kept upon a

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LIST OF EXPERIMENTS IN PHYSICS

MECHANICS

. **The Vernier.** (Watson, Text-Book of Physics, pp. 17.) Practise reading with three different styles of nier. Set it at random and then read it. After you e become familiar with the method of using it, ask the tructor to check your readings.

2. **The Vernier Caliper.** The Vernier Caliper is an trument for measuring the length of a small object. consists of a bar of steel having a fixed arm and a mov- e arm. The object to be measured is placed between two arms, and the distance between them read off a scale engraved on the bar. On the movable arm is duated another scale, called a *Vernier*, which for a en distance has one more division than the fixed scale. enables one to read to a fraction of the smallest division the fixed scale. If there are n divisions on the Vernier $n - 1$ on the bar, we can read to $\frac{1}{n}$ of a division on the r. To read the fraction of a division on the bar, we note at line on the Vernier is opposite a line on the fixed ale. If the number of this line is a, then the length of e object is equal to the number of whole divisions plus e fractional part $\frac{a}{n}$.

The *zero reading* is the reading of the caliper when the ms touch each other. This should be taken every time e caliper is used in case there is some error in its construction, or that it has been strained in some way and the zero line displaced.

Determine the dimensions of three small metal cylinders, with the Vernier Caliper, and from their dimensions, calculate their volumes. Take three readings of the length, and six of the diameter, for each cylinder. The measurements of the diameter should be taken in pairs, the two readings of a pair being taken at right angles to each other to correct for any ellipticity of the cross-section of the cylinder.

A sample set of results for this experiment is given on page 3, in order that the student may see how they should be displayed.

***3. The Micrometer Caliper.** The Micrometer Caliper is an instrument for measuring small distances by means of the number of turns or fraction of a turn made by a screw. It consists of an accurately made screw turning in a nut to which is attached, by means of a curved arm, a piece of steel with a flat face called an anvil. The object to be measured is placed between the end of the screw and the anvil, and the distance between them read off on a scale engraved on the nut. Fractions of the smallest division on the nut are read off on a scale on the edge of a sleeve attached to the screw.

When making a reading the student should estimate by the eye to a tenth part of the smallest division on the sleeve.

In fact, it is a general rule, that when reading a physical instrument the student should read, by estimation, to a tenth part of the smallest division engraved upon it.

Determine the mean diameters of three wires, in the manner described. At least six readings should be made of the diameter of each wire. These readings should be

Example. *October 3d, 1906.*

EXPERIMENT 2

To Find the Volume of a Cylinder with a Vernier Caliper

	Length in Centimeters			Diameter in Centimeters			Mean Length in Centimeters	Mean Diameter in Centimeters	Volume = $\pi r^2 l$ in Cubic Centimeters
	Zero Reading	Reading on Cylinder	Difference	Zero Reading	Reading on Cylinder	Difference			
Cylinder No. 1				.00	1.27	1.27			
				.01	1.27	1.26			
	.00	3.02	3.02	.01	1.27	1.26			
	.01	3.02	3.01	.01	1.26	1.25	3.01	1.263	3.78
	−.01	3.00	3.01						
				−.01	1.26	1.27			
				.00	1.27	1.27			
Cylinder No. 2				.00	1.00	1.00			
				−.01	1.00	1.01			
	.00	2.20	2.20	.02	1.01	.99			
	.00	2.21	2.21	.00	1.00	1.00	2.20	1.00	1.73
	.01	2.20	2.19						
				.00	1.01	1.01			
				.00	.99	.99			
Cylinder No. 3				.01	.88	.87			
				.00	.87	.87			
	.00	1.64	1.64	.00	.88	.88			
	.01	1.65	1.64	.00	.88	.88	1.64	.87	.975
	−.01	1.63	1.64						
				.00	.86	.86			
				−.00	.85	.86			

taken in pairs, the two readings of a pair being at right angles to each other. A sample set of results for this experiment is given on the next page.

EXAMPLE. *October 5th, 1906.*

EXPERIMENT 3

TO DETERMINE THE DIAMETER OF A WIRE WITH THE MICROMETER CALIPER

Zero Reading	Reading on the Wire	Difference in Centimeters	Mean Diameter in Centimeters
Wire No. 1			
—.0006	.0800	.0806	
—.0007	.0795	.0802	
—.0005	.0802	.0807	.0805
—.0006	.0801	.0807	
—.0007	.0798	.0805	
—.0006	.0797	.0803	
Wire No. 2			
—.0006	.1650	.1656	
—.0007	.1651	.1658	
—.0005	.1649	.1654	.1657
—.0007	.1647	.1654	
—.0006	.1655	.1661	
—.0007	.1650	.1657	
Wire No. 3			
—.0007	.2765	.2772	
—.0006	.2762	.2768	
—.0007	.2767	.2774	.2771
—.0007	.2768	.2775	
—.0006	.2764	.2770	
—.0007	.2762	.2769	

4. **The Protractor.** (Stewart and Gee, Volume I, Lesson XIV.) Construct a graduated circle, in the manner described in the reference.

*5. **The Spherometer.** (Sabine, page 7.) Determine the radius of curvature of a convex, or concave, lens or mirror.

Make at least five readings at different places on the lens, taking a new zero reading on the glass plate each time.

EXAMPLE. *October 10th, 1906.*

EXPERIMENT 5

TO FIND THE RADIUS OF CURVATURE OF A LENS WITH A SPHEROMETER

Reading to determine *a*

Zero Reading	Reading on Lens	Difference in Centimeters	Mean *a* in Centimeters
.0025	.0565	.0540	.0546
.0025	.0570	.0545	
.0030	.0578	.0548	
.0026	.0576	.0550	
.0025	.0571	.0546	

Reading to determine *d*

2.48 cm.
2.47 cm. mean $d = 2.48$ cm.
2.50 cm.

$$\text{Therefore } R = \frac{a^2 + d^2}{2a} = 56.3 \text{ cm.}$$

6. **Measurement of Length with the Linear Dividing Engine.** (Stewart and Gee, Volume I, Lesson VI.)

7. **Construction of a Scale with the Linear Dividing Engine.** (Stewart and Gee, Volume I, Lesson VII.)

8. **The Circular Dividing Engine.** (Miller, Experiment VI, § 25.)

9. **The Planimeter.** (Miller, Experiment XI, §§ 35, 36.)

*10. **The Level Tester.** (Miller, Experiment X, § 34.) Determine the sensitiveness of a Spirit Level in the manner described in the reference.

11. **The Micrometer Microscope.** (Miller, Experiment III, § 21.) Determine the pitch of the screw of the micrometer both in inches and in centimeters, and find the ratio of the inch to the centimeter.

12. **The Comparator.** (Miller, Experiment IV, § 22.) Compare an unknown length with a standard length.

*13. **The Telescope Cathetometer.** (Stewart and Gee, Volume I, Lesson IX.) Having made all the necessary adjustments of the Cathetometer, determine the errors in the readings of a metal scale by comparing it with the cathetometer scale, which may be assumed to be correct. Make readings every five centimeters, and plot a curve showing the corrections to be applied to the metal scale.

14. **The Microscope Cathetometer.** (Ames and Bliss, Experiment X.) This instrument is intended for the measurement of small changes of length of three centimeters or less, to one thousandth part of a millimeter.

15. **The Chronograph.** (Miller, § 68.)

*16. **The Parallelogram of Forces.** (Read Watson, Text-Book, § 66.) Fasten three cords together at a point. Let two of them pass over pulleys while one hangs loose. To the two passing over pulleys attach the weights A and B, and to the one hanging loose, the weight C. If C is not too great the three cords will assume a position of equilibrium. The weights A, B, and C are the three forces acting at the point where the cords are fastened together. The directions of the cords give the directions of the forces.

Measure the angles between the cords with a protractor, and make a diagram in your note-book representing these three forces in the following manner: From a point 0 draw three lines, the angles between them being equal to the angles between the cords. Along these lines, lay off from the point *O* distances proportional to the forces *A*, *B*, and *C*.

Having made this diagram of the forces, on the lines proportional to *A* and *B*, construct a parallelogram, and draw its diagonal. This diagonal, by the Theorem of the Parallelogram of Forces, represents the *resultant* of *A* and *B*. Also since *A* and *B* are balanced by *C*, it represents the *equilibrant* of *C*. If the length of the diagonal is equal to the length of the line representing *C*, and is in the same direction, we have here a proof of the Theorem of the Parallelogram of Forces.

Vary *B* and *C* and make three diagrams in this manner.

17. **Lami's Theorem.** (Miller, Experiment XIII, § 38.)

*18. **Equilibrium of Moments.** (Miller, Experiment XV, § 40.) *First*, determine an unknown mass in the manner described in the reference.

Second, determine the weight of the meter-bar in the manner described.

Make three settings of the weights in each case and take the mean.

*19. **The Law of Falling Bodies.** (Millikan, Experiment I.)

20. **Atwood's Machine.** (Ames and Bliss, Experiment XVI.)

21. **Determination of g with Atwood's Machine.** (Miller, § 62.)

*22. **Law of the Simple Pendulum.** The object of this experiment is to determine the relation of the period of oscillation of a Simple Pendulum to its length.

To do this, let the pendulum swing through a small arc of 5 degrees or less, and find the complete period of oscillation when it is about 100, 70, 40, 30, and 20 centimeters long, respectively. The period can be found by noting the time of 100 complete vibrations with a watch, and then dividing this time by 100. The result is the period, or the time which the pendulum takes to make one complete swing.

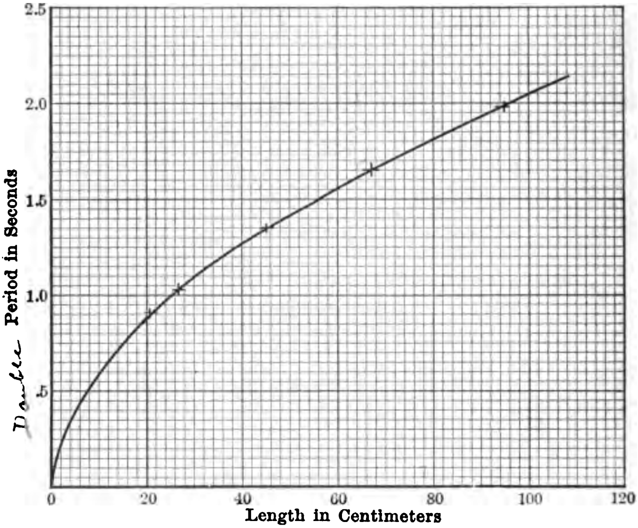

Fig. 1. — Curve Showing Relation of the Period of a Pendulum to its Length

The length of the pendulum can be determined with sufficient exactness for this experiment by measuring the distance from the point of support to the top of the bob, and adding to this the radius of the bob.

With the results that you obtain, plot a curve representing the relation of the period of the pendulum to its length.

Take the lengths as ordinates, and the periods as abscissas. A sample curve is given in the text to illustrate the method of plotting.

Divide the *square* of the period by the length in each case. Is the quotient a constant? If so, what is the relation of the period of a simple pendulum to its length? If this relation holds between the ordinates and abscissas of the curve which you have plotted, what is this curve called?

Record your results in a table of the following form:

Length in Centimeters	Period in Seconds	Period Squared	Period Squared Divided by the Length
94.9	1.98	3.92	.0413
67.0	1.65	2.72	.0406
44.4	1.34	1.79	.0403
27.1	1.03	1.06	.0391
20.2	.91	.82	.0406

*23. **Determination of g with the Simple Pendulum.** (Read Miller, §§ 64, 65.) Make the length of the pendulum approximately 100 centimeters, and perform the experiment as described in Miller, using the Method of Coincidences to determine its period. Close the sounder circuit of the Laboratory clock so that the sounder will tick seconds. You will not then need to use a watch. Count the ticks of the clock between two coincidences, and divide the total time elapsed by the number of coincidences less one, to get the time between two successive coincidences.

It will only be necessary to use one length of pendulum. The distance from the point of support to the bottom of the bob can be measured with a Beam Caliper, and the diameter of the bob with a Vernier Caliper.

Take at least three independent sets of observations, using this length.

Make corrections for,

I. Length of the arc of swing.
II. True length of the equivalent simple pendulum.
III. The error of the Laboratory clock.

This experiment should be recorded as follows:

Date.

EXPERIMENT 22

To Determine *g* (the Acceleration of Gravity) by Means of the Simple Pendulum, Using the Method of Coincidences to Determine the Period of an Oscillation

Total Number of Coincidences	Time between First and Last Coincidences in Seconds	Mean Time between Two Successive Coincidences	Period in Seconds
3	436	145.3	.99316
3	447	149.0	.99333
2	283	141.5	.99298

Distance from the point of support to the bottom of the bob = 100.50 cm.

Radius of the bob = 2.54 cm.

Correction for true length of the equivalent simple pendulum = .026 cm.

Length of the arc = 5°

Correction for length of the arc = .00011 second

Correction for the error of the clock = 0.0

Corrected length = 97.99

Mean corrected period = .9931

$$g = \frac{\pi^2 l}{t^2} = \frac{(3.1416)^2 \times 97.99}{(.9931)^2} = 980.7 \frac{\text{cm}}{\text{sec.}^2}$$

g in Cincinnati is 979.99 $\frac{\text{cm.}}{\text{sec.}^2}$

Therefore the percentage error of this result is .07%

24. **Determination of g by Bessel's Method.** (Stewart and Gee, Volume I, § 166.)

*25. **The Compound Pendulum.** (Hastings and Beach, §§ 62, 63.) Determine by experiment the period of the compound pendulum supplied, and then calculate it from the formula given in the reference, and see how closely the calculated and experimental values agree. In the calculation take into account the weight of the rod.

At what distance from the point of support is the center of gravity of the system?

What is the length of the radius of gyration?

What is the length of the equivalent simple pendulum?

26. **Determination of g with Kater's Pendulum.** (Miller, §§ 66, 67.) The period should be determined by the Method of Coincidences, and the distance between the knife edges measured with the Cathetometer.

*27. **Properties of the Path of a Projectile.** (Miller, Experiment XXIII, § 63.)

28. **Simple Harmonic Motion.** (Millikan, Experiment XI.)

29. **Composition of Simple Harmonic Motion and the Motion of Translation.**

*30. **Composition of Two Simple Harmonic Motions at Right Angles to Each Other.** (Lissajous' Figures.)

Simple Harmonic Motion (written S.H.M.) is the most common form of periodic motion in nature. It is, for example, the motion of a pendulum bob, of the end of a tuning fork, or of the top of a tree swaying in the wind. At the two ends of its path, the body comes to rest, and its speed is greatest at its middle point. The time that the body takes to go from its middle point to one end of its path, back to the middle point, over to the other end of its path and back to its middle point again is called its *Period.* Its *Amplitude* is the distance from its middle point to one end of its swing.

A body may have two simple Harmonic Motions at right angles to each other, at the same time. In this case, it will move in an ellipse or in a path of a more complicated figure. Two S.H.M's are said to be in the same *Phase* when they are at corresponding points of their paths at the same time. If one motion has completed ¼ of its period when the other is just beginning, they are said to differ in phase by ¼ of a period, and so on.

When two S.H.M's at right angles to each other are given to a body at the same time, they are said to be compounded.

The resulting motion of the body may be studied by means of the S.H.M. *table*, in which the motion of a stylus or pen is given by two pendulums swinging at right angles to each other, and the stylus or pen makes a trace upon a piece of smoked glass or some other suitable object.

Using such a table, determine by experiment the figures formed by two harmonic oscillations at right angles to each other, having equal amplitudes, and having the following ratios of periods and differences of phase:

Periods	*Difference of phase*
1 : 1	0
1 : 1	¼
1 : 2	0
1 : 2	¼
1 : 2	½
2 : 3	0
2 : 3	⅛

The difference in period can be obtained by adjusting the positions of the weights.

In some way, make a permanent record of these figures, by using a pencil as the moving point, or by making the figures on smoked glass and then making blue-prints of them, or by making drawings of the figures directly in the note-book. Paste any figures so obtained in the note-book, marking on each one the period ratio, and the phase difference.

*31. **Coefficient of Friction.** (Ames and Bliss, Experiment XXV.)

*32. **The Use of the Mercury Barometer.** (Ames and Bliss, pages 157–159.) Make a careful reading of the Mercury Barometer, using the attached Vernier, and reduce this, by means of Table IX, p. 522 in the reference, to zero degrees centigrade, and latitude 45 degrees.

33. **To determine the Errors of an Aneroid Barometer.** (Miller, Experiment XXXIV, § 88.)

*34. **Reading a Balance by Vibrations.** (Sabine, pages 10, 11.)

*35. **Sensitiveness of a Balance.** (Stewart and Gee, Volume I, § 65 (γ).)

*36. **Double Weighing with the Balance.** (Sabine, pages 12, 13.)

*37. **Weight *in vacuo* with a Balance.** (Sabine, pages 13–15.)

*38. **Young's Modulus by sketching a Wire.** (Millikan, pages 67–70.)

39. **Young's Modulus by the Bending of a Beam supported at Both Ends.** (Stewart and Gee, Volume I, § 124.) Determine by this method Young's Modulus for Steel, using a rod of square cross-section.

Take readings of the bendings produced by the addition of loads increasing successively by 500 grams each time.

Take observations for five different loads, and then take readings diminishing the load by 500 grams each time.

From the deflections so obtained, calculate the value of Young's Modulus.

The breadth and depth of the steel rod should be determined with a micrometer caliper, as it is necessary that these quantities should be measured as accurately as possible. Take three readings of each quantity at different points of the rod, and take the means.

Plot a curve showing the relations of the deflections to the loads. Plot loads as abscissas and deflections as ordinates. Does the curve so obtained confirm Hooke's law?

State in words what is meant by Young's Modulus.

40. **Young's Modulus by the Bending of a Beam supported at One End.** (Stewart and Gee, Volume I, § 125.)

41. **Poisson's Ratio by stretching.** (Stewart and Gee, Volume I, § 131.)

42. **Tenacity.** (Stewart and Gee, Volume I, §§ 133, 134.)

43. **The Law of Centrifugal Force by Millikan's Method.** (Millikan, Experiment XIII.)

44. **The Law of Centrifugal Force by the Method of Ames and Bliss.** (Ames and Bliss, Experiment XVII.)

45. **The Ballistic Pendulum.** (Miller, Experiment XIV, § 39.)

49. **The Laws of Torsion.** (Miller, § 81.)

47. **Moment of Inertia by the Torsion Pendulum.** (Sabine, pages 20–23.)

*48. **Coefficient of Rigidity with the Torsion Lathe.** (Miller, § 80.)

49. **Coefficient of Rigidity with the Torsion Pendulum.** (Ames and Bliss, Experiment XXVIII.)

50. **Moment of Force and Angular Acceleration.** (Duff, Experiment XVII.)

51. **Conservation of Angular Momentum.** (Duff, Experiment XVIII.)

*52. **Moment of Inertia.** (Millikan, Experiment X.)

53. **Density of a Solid by measuring its Weight and Volume.** (Kohlrausch, § 13, I, B, 1, page 46.)

*54. **Specific Gravity of Solids with the Hydrostatic Balance.** (Ames and Bliss, Experiment XXXI.)

*55. **Specific Gravity of Solids with Jolly's Balance.** (Miller, Experiment XLIV, § 102.) The Jolly Balance depends for its action upon Hooke's Law, which says that, for elastic bodies, the elongation is proportional to the stretching force. Since a helical spring is an elastic body, it obeys this law.

The experiment may profitably be divided into two parts, namely, (i) to verify Hooke's Law, and (ii) to determine the Specific Gravity of one or more solids.

i. *To Verify Hooke's Law.* Level the instrument carefully. Then bring the index to zero, and measure with a meter stick the distance between the fixed and movable marks. Estimate to tenths of a millimeter. Add successive weights of the values 1, 2, 3, 4, and 5 grams respectively, and record the elongation of the spring in each case. Divide each of these elongations by the weight which produced it. If the experiment has been performed carefully, the quotient will be the same in each case. This shows that the elongation varies directly as the stretching force, and that Hooke's law holds for a helical spring.

Plot a curve showing the relation between the stretching force and the resultant elongation. Plot the weights as abscissas and the elongations as ordinates. Since the elongation varies directly as the stretching force, the resultant curve should be a straight line. The elongation is therefore said to be a *linear function* of the stretching force.

ii. *To Determine the Specific Gravity of Solids.* Use the instrument as explained in the reference to determine the Specific Gravity of two or more solids.

56. **Specific Gravity of Solids with Nicholson's Hydrometer.** (Ames and Bliss, Experiment XXXII.) Determine with this instrument the density of lead, nickel, coin silver, copper, brass, iron, and aluminum. Make the determination of these specific gravities just as accurately as you can with this instrument. Be on the alert to detect all possible sources of error, and perform the experiment with great care.

57. **Specific Gravity of Solids with the Pyknometer.** (Miller, § 97, *Density of a Solid in Fragments.*)

*58. **Density of Liquids with the Pyknometer.** (Stewart and Gee, Volume I, Lesson XXXII.) Make, by this method, an *exact* determination of the density of alcohol. Weigh to tenths of a milligram by the method of vibrations; use the method of double weighing; and make corrections for the buoyancy of the air.

59. **Specific Gravity of Liquids with Mohr's Balance.** (Stewart and Gee, Lesson XXXVI, Method III.) This instrument gives the Specific Gravity of Liquids directly in terms of water at 15° C.

Determine the densities of five different liquids, as for example, of Alcohol, Kerosene, Turpentine, Olive Oil, and Glycerine.

60. **Specific Gravity of Liquids with Baumé's Hydrometer.** (Stewart and Gee, Volume I, § 97.) Make a 2, 4,

6, 8, and 10 per cent. solution of common table salt (sodium chloride), and determine the density of each solution by means of a Baumé Hydrometer. Record your results in degrees Baumé, and also in terms of absolute density. The relation of absolute density to degrees Baumé may be found in Table Q in the reference. A 2 per cent. solution means 2 parts by weight of salt to 98 parts by weight of water. Observe and record the temperature of the solution in each case.

With the results that you obtain from this experiment, plot a curve showing the relation of the absolute densities of the solutions to their concentrations. Take concentrations for abscissas, and absolute densities for ordinates.

61. **Specific Gravity of Liquids with Balancing Columns.** (Miller, § 100.) Determine the Specific Gravity of Mercury by this method, using a meter stick to measure the heights of the liquid columns. Measure to the highest point of the Mercury meniscus, and to the lowest point of the water meniscus. Make the lengths of the balancing columns as great as possible, for the longer they are, the more accurate will be the results. Make all the measurements very carefully, otherwise the value obtained for the density will not be satisfactory.

62. **Density of Air by Exhaustion.** (Miller, Experiment XLI, § 98.)

63. **Density of a Gas by weighing.** (Miller, Experiment XLII, § 99.)

64. **Velocity of Efflux of a Liquid: Torricelli's Theorem.** (Ganot's Physics, § 142.)

65. **Flow of Liquids in Tubes: the Pressure Head.** (Barker, § 182.)

*66. **Boyle's Law.** (Miller, Experiment XXXIII, § 87.)

67. **To Determine the Gas Constant.** (Hastings and Beach, § 138.)

68. **The Angle of Contact.** (Hastings and Beach, § 108.) Determine the angle of contact of mercury with glass by varying the *inclination* of a glass plate immersed in mercury until the line of contact between the mercury and the glass lies in the plane of the surface of the mercury, on one side of the glass plate. In order to get good results, the glass plate and the mercury must *both* be very clean. Clean the glass plate first with dilute nitric acid, and then with a solution of caustic soda. This is best done with a small swab made of a piece of clean linen rag tied around the end of a small glass rod. Take six readings altogether; three readings turning the plate downward from the vertical position, and three readings turning it upward from the horizontal.

*69. **Surface Tension with Capillary Tubes.** (Miller, Experiment XXXVI.) Perform the experiment as described in the reference, using two capillary tubes of different internal diameters. Determine the Surface Tension of both water and alcohol.

Remember that the complete formula for surface tension as deduced from the rise of a liquid in a capillary tube is given by

$$T = \frac{h \rho r g}{2 \cos a}$$

where

T is the surface tension.
h, the height of rise of the liquid in the tube.
ρ, the density of the liquid.
r, the radius of the tube.
g, the acceleration of gravity.
a, the angle of contact for the liquid used.

For water $\rho = 1$.

For alcohol $\rho = .79$.

For water in contact with glass in air $a = 0$.

For alcohol in contact with glass in air $a = 0$.

For mercury in contact with glass in air, a is equal to about 136°. Therefore the surface of mercury is depressed in a capillary tube.

70. **Surface Tension by Direct Measurement.** (Miller, Experiment XXXVII, § 92.) Find by this method the surface tension of two liquids; for example, of water and of alcohol.

*71. **Coefficient of Viscosity by the Rate of Flow through Small Tubes.** (Kohlrausch, Experiment 37 C.) Before beginning this experiment the student should read § 183 in Barker's Physics.

Determine by the method described in Kohlrausch the Coefficient of Viscosity of water. Distilled water should be used for this experiment, and a correction made for the velocity of flow in the capillary tube. If the outer end of the tube is immersed in the water in the receiving vessel, the total height h is the distance from the surface of the water in the reservoir to the surface of the water in the receiving vessel. The radius of the capillary tube can be determined by drawing into it a thread of mercury from ten to twenty centimeters long, placing this thread in three positions along the tube, and measuring its length in each position. The mean of the three lengths is then taken and the mercury is taken out of the tube and weighed. From the length and weight of the thread and the density of mercury, the mean radius of the tube can easily be calculated.

72. **Coefficient of Viscosity with the Torsion Pendulum.** (Miller, Experiment XXXVIII, § 93.)

73. **Compressibility of a Liquid with the Piezometer.** (Miller, Experiment XXXII, § 86.)

74. **The Pressure of Moving Air.**

75. **Change of Volume with Solution.**

SOUND

76. **Transmission of a Wave along a Heavy Cord.**

77. **Transmission of a Wave along a Helical Spring.** (Ames and Bliss, Experiment XXXVIII, Part 1.)

78. **Transmission of a Wave on the Surface of Water.** (Ames and Bliss, Experiment XXXVIII, Part 2.)

*79. **Laws of Vibrating Strings with the Sonometer.** (Miller, § 119.)

80. **Melde's Experiment.** (Stewart and Gee, Volume III, Experiment LXIII.)

81. **Transverse Vibrations of a Rod fixed at One End.** (Stewart and Gee, Volume III, Experiment XL.)

82. **Transverse Vibrations of a Rod Free at Both Ends.**

83. **Longitudinal Vibrations of a Rod.**

84. **Properties of a Tuning Fork.** (Stewart and Gee, Volume III, Experiments XLVIII–LIV.)

*85. **Frequency of a Tuning Fork with the Monochord.** (Sabine, Experiment VII, pages 24–26.)

*86. **Frequency of a Tuning Fork with the Chronograph.** (Miller, Experiment LII, § 108.)

87. **Frequency of a Tuning Fork with the Stroboscope.** (Kohlrausch, XXXVII A (2).)

88. **Frequency of a Tuning Fork by Lissajou's Figures.** (Miller, § 109.)

89. **Frequency of a Tuning Fork by the Method of Beats.** (Glazebrook and Shaw, Experiment XXVII.)

90. **Frequency of a Tuning Fork by Optical Comparison.** (Miller, §§ 112, 113.)

91. **Properties of a Vibrating Column of Air.** (Ames and Bliss, Experiment XLIII.)

92. **Frequency of an Organ Pipe with the Siren.** (Stewart and Gee, Volume III, Experiment XXXVIII.)

93. **Determination of the Overtones in an Organ Pipe.** (Sabine, Physical Measurements, First Edition, Experiment XXIII.)

94. **The Properties of Vibrating Plates.** (Stewart and Gee, Volume III, Experiments XLII–XLVII.)

*95. **Velocity of Sound in Air, with Tube and Diaphragm.** (Sabine, Experiment VII, pages 28, 29.)

96. **Velocity of Sound in Air, with Tube and Water.** (Ames and Bliss, Experiment XL.)

97. **Velocity of Sound in Air by Interference.** (Miller, Experiment LVII, § 118.)

*98. **Velocity of Sound in Metals with Kundt's Dust Figures.** (Sabine, Experiment VII, pages 29–31.)

99. **Velocity of Sound in a Gas.** (Miller, Experiment LVII, § 118.)

100. **Relative Velocity of Sound in Metals.** (Ames and Bliss, Experiment XLII.)

101. **Young's Modulus with Kundt's Dust Figures.** (Miller, § 117.)

102. **Young's Modulus for the Steel of a Tuning Fork.** (Stewart and Gee, Volume III, Experiment LX.)

103. **Energy of Vibration of a Tuning Fork.** (Stewart and Gee, Volume III, Experiment LXI.)

104. **Determination of g with a Tuning Fork.** (Stewart and Gee, Volume III, Experiment LXIV.)

105. **The Structure of the Musical Scale.** (Sabine, Experiment VII, pages 26, 27.)

106. **Quality by the Manometric Flame.** (Sabine, Experiment IX.)

107. **Composition of a Sound with Resonators.** (Miller, § 124.)

108. **Properties of Singing Flames.** (Stewart and Gee, Volume III, Experiments CXIX–CXXI.)

109. **Properties of Sensitive Flames.** (Stewart and Gee, Volume III, Experiments CXXV–CXXVII.)

110. **Determination of Wave-length with a Sensitive Flame.** (Glazebrook and Shaw, Experiment XXXI.)

HEAT

*111. **Determination of the Fixed Points of a Mercury Thermometer.** (Ames and Bliss, Experiment XLIV.)

112. **Calibration of the Bore of a Mercury Thermometer.** (Miller, § 129.) Plot a curve showing the corrections to be applied to the reading of the thermometer on account of the variation in the bore of the tube. Take thermometer readings for abscissas and corrections for ordinates.

*113. **The Constant Volume Air Thermometer.** (Miller, § 134.) Determine with this instrument the temperature of the Laboratory, and also the Coefficient of Pressure for air.

Be very careful not to break off the glass bulb, and, also, not to allow the mercury to run over into it.

114. The Constant Pressure Air Thermometer. (Preston, § 92.)

115. The Weight Thermometer. (Preston, § 77.)

116. The Pyrometer.

***117. Vapor Density by Dumas' Method.** (Kohlrausch, § 16 A, or Watson, Text-Book, page 245.) Determine, by this method, the density of Ether Vapor.

Since Ether boils at 34.9° C., a water bath may be used. The moment at which all the ether is vaporized may be determined by lighting the issuing jet. When the liquid is completely vaporized the flame becomes very small. The bulb should then be immediately sealed, and a reading taken of the temperature of the bath. The water in the bath should be stirred continuously so as to make the temperature uniform throughout.

The results should be recorded as follows:

Date.

EXPERIMENT 210

TO DETERMINE THE RELATIVE VAPOR DENSITY OF ETHER BY DUMAS' METHOD

m = Weight of bulb full of air =
m' = Weight of bulb full of ether vapor =
M = Weight of bulb full of water =
t = temperature of vapor at moment of sealing =
b = barometric pressure at moment of sealing =
t' = temperature of air in balance case when vapor was weighed =
b' = barometric pressure when vapor was weighed =
λ' = density of air at t' degrees and b' centimeters (taken from the tables) =

Relative Density of Ether Vapor =

$$\left(\frac{m'-m}{M-m}\cdot\frac{1}{\lambda'}+1\right)\quad\left(\frac{b'}{b}\cdot\frac{1+.00367\,t}{1+.00367\,t'}\right)=$$

***118. Vapor Density by Mayer's Method.** (Hastings and Beach, § 257.) Determine the relative vapor density of some volatile liquid, such as ether or chloroform, by this method.

If ether is used, since it boils at 34.9° C., water may be used in the outer tube. The water should be made to boil violently so that the temperature of the bath may be uniform throughout its length. Before beginning the experiment, the old asbestos should be taken out of the inner tube, and all ether vapor or water which may have been left in it from some previous experiment should be sucked out with the suction pump. Since the ether in the small flask, which is dropped into the inner tube, evaporates very rapidly, the flask should be weighed full at the convenience of the experimenter, and then filled up again just before dropping it into the tube. The flask should be handled with a pair of forceps and *not* with the fingers, as the heat of the fingers will cause the ether to evaporate.

After the experiment is finished, be sure to remove the rubber stopper from the end of the inner tube, otherwise water will be sucked back into it, as the vapor inside it cools.

The results should be recorded as follows:

Date.

EXPERIMENT 211

TO DETERMINE THE RELATIVE DENSITY OF ETHER VAPOR BY MAYER'S METHOD

Weight of empty flask =
Weight of flask filled with ether =
Weight of the ether =
Temperature of the room =
Barometric pressure =
Pressure of the water vapor within the tube =
Volume of air displaced =
Relative Density of Ether Vapor =

*119. **Vapor Tension by Dalton's Method.** (Ames and Bliss, Experiment LV, Method 2.) Determine by this method the vapor tension of some volatile liquid, such as ether or chloroform, for five different temperatures, between 50° C. and the temperature of the room. To do this, begin with the water in the water jacket at a temperature of about 50° C., and allow it to cool to the temperature of the room. To get good results, the water in the water jacket should be kept well stirred, and both *the tube and the mercury should be perfectly clean and dry before beginning the experiment.*

Plot a curve with the results obtained showing the relation between vapor tension and the temperature. Plot temperatures as abscissas, and tensions as ordinates.

120. **Vapor Tension of Solutions.** (Kohlrausch, § 27 A.)

121. **Coefficient of Linear Expansion with the Lever and Scale.** (Ames and Bliss, Experiment XLV.)

*122. **Coefficient of Linear Expansion with the Micrometer Screw.** (Whiting, Volume I, ¶57.)

123. **Coefficient of Linear Expansion with the Comparator.** (Miller, § 125.)

124. **Coefficient of Cubical Expansion of Solids.** (Ames and Bliss, Experiment XLVII.)

*125. **Coefficient of Apparent Cubical Expansion of Mercury with the Weight Thermometer.** (Hastings and Beach, § 127.) Determine the apparent expansion of mercury in glass with the Weight Thermometer in the manner described in the reference.

For this purpose, construct a Weight Thermometer having a bulb about two inches long and half an inch wide. Fill it with mercury by alternately heating it and allowing the mercury to be sucked up into it as it cools. After it is filled, immerse the bulb in water at the temperature of the room. Determine the temperature of the water and then gradually heat the water until it boils. Collect the mercury driven off as the temperature of the water rises and weigh it. The water should be stirred continuously.

The results may be recorded as follows:

Date.

EXPERIMENT 231

TO DETERMINE THE COEFFICIENT OF APPARENT CUBICAL EXPANSION OF MERCURY WITH A WEIGHT THERMOMETER

m = weight of mercury driven off =
W = weight of thermometer with mercury remaining in it =
w = weight of thermometer empty =
t_1 = temperature of the cold water =
t_2 = temperature of the boiling water =
Coefficient of apparent cubical expansion of mercury in glass

$$= \frac{m}{(W - w)\ (t_2 - t_1)}$$

***126. Coefficient of Cubical Expansion of Liquids with the Pyknometer.** (Sabine, Experiment XXVI.)

127. **Coefficient of Cubical Expansion of Liquids by the Method of Equilibrating Columns.** (Preston, § 114.)

128. **Coefficient of Cubical Expansion of Liquids with the Dilatometer.** (Miller, § 127.)

129. **The Law of Charles, or Gay-Lussac.** (Watson, Text-Book, § 194.)

130. **Coefficient of Cubical Expansion of Gases.**

*131. **To determine the Temperature of the Greatest Density of Water.**

*132. **Specific Heat of Solids by the Method of Mixtures.** (Ames and Bliss, Experiment XLIX.)

133. **Specific Heat by the Method of Cooling.** (Kohlrausch, § 30.)

*134. **Specific Heat of a Solid by Black's Method.** (Miller, Experiment LXXVII, § 142.)

*135. **Specific Heat with the Ice Calorimeter of Lavoisier and Laplace.** (Ganot, § 459.)

*136. **Specific Heat with the Ice Calorimeter of Bunsen.** (Miller, § 143.)

137. **Specific Heat with the Steam Calorimeter of Joly.** (Preston, §§ 136, 137.)

*138. **Ratio of the Two Specific Heats of a Gas by the Method Clement and Desormes.** (Preston, § 147.)

*139. **Latent Heat of Fusion of Ice.** The Latent Heat of Ice is the amount of heat, measured in calories, required to convert one gram of ice, at the temperature of its melting point, into water. It can be determined by melting a known mass of ice at 0° C. in a known mass of water at $t_1°$, in a calorimeter, and finding the fall of temperature of the water. The amount of heat taken from the water to melt the ice can then be found at once by multiplying the mass of the water by its fall of temperature. Since, however, as the ice melts and the water cools, the calorimeter itself gives up heat to the water, this heat must be added to that given up by the water. The amount of heat given up by the calorimeter when its temperature falls one degree, called its *thermal capacity*, can, perhaps, be best obtained by weighing the calorimeter when dry and multiplying it by the specific heat of the metal of which it is made. The total amount of heat contributed by the calorimeter to melting the ice is found by multiplying its thermal capacity by its fall of temperature.

Let the water in the Calorimeter be at about 30° C. when you begin the experiment, and add ice until it has been cooled to about 10° C. You will thus start with the temperature of the water about 10° above, and cool it to about 10° below the temperature of the room. In this way, you will largely get rid of the error due to radiation, and to convection currents in the air. The pieces of ice used should be about the size of small walnuts, and the student should be careful that the ice is dry before putting it into the calorimeter. The quantity of ice put in can be determined by weighing the calorimeter and its contents at the beginning of the experiment before any ice is put in, and again at the close of the experiment. The difference between these two weights will be the weight of the ice melted. If

m_1 = mass of water in calorimeter at beginning.
m_2 = mass of ice added.
a = Thermal capacity of calorimeter.
L = Latent Heat of ice.
t_1 = temperature of water in calorimeter at beginning.
t_2 = final temperature of water.

Then

$$\begin{aligned} L\,m_2 + m_2t_2 &= m_1\,(t_1 - t_2) + a\,(t_1 - t_2) \\ &= (m_1 + a)\,(t_1 - t_2) \end{aligned}$$

and

$$L = \frac{(m_1 + a)\,(t_1 - t_2)}{m_2} - t_2$$

*140. **Latent Heat of Vaporization of Water.** (Miller, Experiment LXXXIV, § 149.)

141. **The Melting Point of a Simple Body.** (Ames and

Bliss, Experiment LI.) Determine the melting point of paraffin. Instead of using the capillary tube described in the reference, put the paraffin in a small test tube and place the thermometer directly in it.

142. **The Melting Point of a Solution.** (Kohlrausch, § 26 A.)

143. **The Melting Point of a Solution with Beckmann's Apparatus.** (Watson, § 225.)

144. **The Boiling Point of a Simple Body.** (Ames and Bliss, Experiment LIII.)

*145. **The Boiling Point of a Solution.** Make up a 5, 10, 15, 20, and 25 per cent. solution of common table salt (Sodium Chloride), and determine the boiling point in each case.

With your results, plot a curve showing the variation of the boiling point with the concentration, using concentrations for abscissas, and boiling points for ordinates.

146. **Relation of the Boiling Point of Water to the Pressure for Pressures greater than One Atmosphere.** (Ganot, § 391.) This can be determined by confining the water in an air-tight vessel, known as Papin's Digester, provided with a manometer to measure the pressure of the steam, and a thermometer to measure the temperature of the water. The water is slowly heated and the pressures corresponding to the rising temperatures noted. The vessel is provided with a safety valve so that the pressure cannot rise above a certain value. Since a state of equilibrium must be constantly maintained between the water and the steam, the temperature corresponding to any pressure gives the boiling point for this pressure.

The student should observe about ten pairs of values for corresponding pressures and boiling points, and plot a curve showing the relation between them. From the curve he should deduce the relation between the pressure and the boiling point of a liquid.

*147. **The Critical Temperature.** The Critical Temperature is that temperature at which a substance refuses to remain a liquid however great the pressure may be. At this temperature the differences between the vapor and the liquid of a substance disappear, so that they both have the same density and cohesive properties. Consequently at this temperature the meniscus becomes flat, and ultimately disappears.

A small glass tube hermetically sealed is about half full of ether. This tube is completely immersed in a bath of melted paraffin which is gradually heated to nearly 200° C. The critical temperature can be determined by noting the temperature at which the meniscus disappears. An observation should be made as the meniscus disappears with rising temperature, and also as it reappears again as the ether cools. The mean of the two readings will give the best value. At least three independent sets of reading should be made.

*148. **Thermal Conductivity of Solids with Searle's Apparatus.** The thermal conductivity of a substance is the amount of heat passing between opposite faces of a unit cube of the substance, during one second, when they differ in temperature by one degree centigrade. The following account of Searle's apparatus is taken from his paper in the *Philosophical Magazine* for January, 1905, by the kind permission of the author and of Messrs. Taylor and Francis.

The principle of continuous flow calorimetry is employed in the method. One end of a stout bar of copper is heated by steam, while the other end is kept cool by a stream of water flowing through a narrow copper tube soldered to that end of the bar, and means are provided for determining the temperatures of two intermediate points on the bar. When in addition to these two temperatures the difference of temperature between the inflowing and outflowing water and also the mass of water flowing through per second are known, the conductivity of the copper is easily calculated.

The apparatus is shown diagrammatically in Fig. 2, page 32. The copper rod XY is about 20 cm. long and about 2.5 cm. in diameter. To the end X is fixed a small copper cylinder, closed at the ends, and steam from a small boiler passes through this cylinder. It is convenient to place the boiler below the level of the cylinder and to make the steam-pipe large enough to allow the water formed by the condensation of the steam to find its way back to the boiler. At the top of the cylinder the surplus steam passes out by a small escape pipe. A copper tube, 2 mm. in internal diameter, is coiled four times round the end Y and is soldered to the rod; this tube serves to convey the cooling water.

The temperatures of the water before and after passing through the coiled tube are ascertained by means of the thermometers D and C, which are fixed into the small copper vessels H and G by cork or india-rubber stoppers. Water enters H by the tube P and leaves G by the tube Q, the necessary connections being completed by the india-rubber joints I, I. A convenient way of obtaining a steady flow of water is to allow the inflow pipe attached to P to dip like a siphon into a reservoir in which the water is kept just overflowing by a stream from a tap. By changing the difference of level between the surface of the water in the reservoir and the lower end of the outflow tube O, the current of water can be easily varied. With the apparatus in use in my own class the difference of level is never greater than 1 meter. The flow is easily started by sucking the end of the tube O.

The mass of water which flows through per second is readily found by observing the time taken to fill a 250 ccm. flask. The water is, of course, allowed to flow continuously, and the time is counted from the instant when the flask is brought up to receive the water.

If, when the conditions have become steady, the temperature

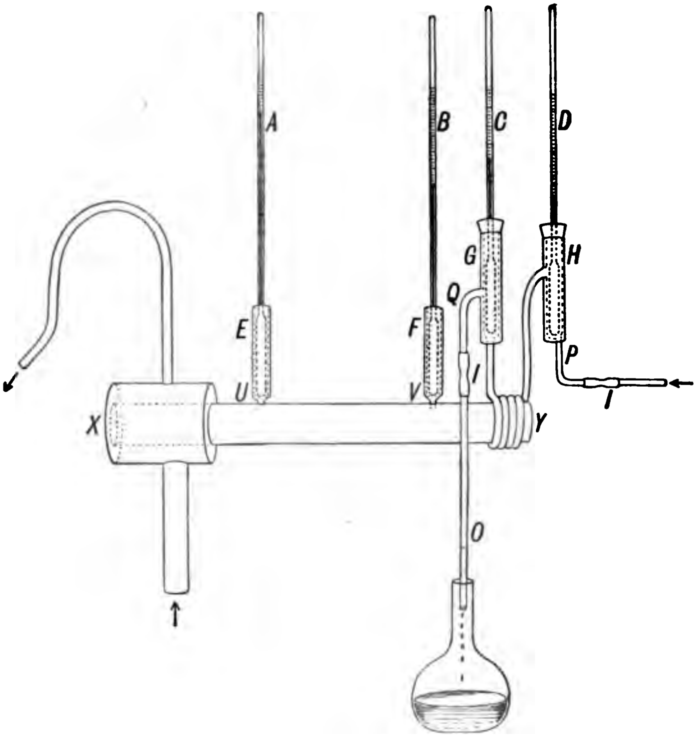

Fig. 2

of the water in *H* be θ_4 and that of the water in *G* be θ_3, and if *M* grams of water flow through in *t* seconds, then heat is taken away by convection from the end *Y* at the rate of

$$\frac{M(\theta_3 - \theta_4)}{t} \text{ thermal units per second.}$$

To determine the temperature-gradient along the part of the rod between the steam-jacket and the cooling-tube, we must know the temperatures at two points on the bar separated by a measured interval. These temperatures are found by means of the thermometers A, B, which fit loosely into holes bored in the stout copper rods E, F, nearly to the lower ends of the rods. The lower ends of these rods are cut away so as to fit into saw-cuts made in the bar at U and V, and the rods are secured to the bar by solder or, preferably, by brazing. If no heat escapes from the copper tubes, the thermometers placed within them will indicate the temperatures of the bars at U and V. The distance between U and V is about 10 cm. in my apparatus. The isothermal surfaces passing through U and V are supposed to be plane. To secure this approximately, the distances of U and V from the steam-jacket and the cooling-tube respectively are not less than the diameter of the bar.

If θ_1 be the temperature at U and θ_2 that at V, when the conditions have become steady, and if the cross-section of the bar be A square cm. and the distance between the centers of the saw-cuts at U and V be l cm., then the rate at which heat flows along the bar is

$$\frac{K(\theta_1 - \theta_2)A}{l} \text{ thermal units per second,}$$

where K is the thermal conductivity.

Equating this to the former value, we have

$$K = \frac{Ml}{At} \cdot \frac{\theta_3 - \theta_4}{\theta_1 - \theta_2}$$

It has been assumed in this calculation that all the heat which flows across the section of the bar at U flows also across the section at V, and that the whole of this heat is absorbed by the cooling water. To obtain a practical approximation to this ideal condition, the whole bar with its fittings is very thickly wrapped from end to end with a woollen covering. Wool or felt is also wrapped round the copper tubes E F and round the vessel G. It is not necessary to wrap up the vessel H, as this vessel is in practice at nearly the atmospheric temperature. For convenience, the apparatus, when wrapped with wool, is placed in a wooden box provided with feet.

On account of the high conductivity of copper and the large cross-section of the bar, the heat conducted along the bar is very large compared with that which escapes altogether from the bar and with that which passes from one end of the bar to the other by conduction through the woollen covering.

To illustrate the working of the apparatus, I give the numerical details of an experiment in which two different rates of flow of water were used.

$$A = 5.267 \text{ cm.}^2 \qquad l = 9.95 \text{ cm.} \qquad M = 250 \text{ gm.}$$

(*a*) θ_1 82° .0 C., $\theta_2 = 44°.8$ C., $\theta_3 = 23°.1$ C., $\theta_4 = 12°.5$ C. $t =$ 155.5 sec.

$$\text{Hence} \quad K = \frac{250 \times 9.95}{5.267 \times 155.5} \cdot \frac{10.6}{37.2} = .865 \frac{\text{calories}}{\text{cm.}^2 \times \dfrac{\text{degrees}}{\text{cm.}} \times \text{sec.}}$$

(*b*) $\theta_1 = 80°.8$ C., $\theta_2 = 40°.9$ C., $\theta_3 = 17°.3$ C., $\theta_4 = 12°.8$ C. $t = 65.6$ sec.

$$\text{Hence} \quad K = \frac{250 \times 9.95}{5.267 \times 65.6} \cdot \frac{4.5}{39.9} = .812 \frac{\text{calories}}{\text{cm.}^2 \times \dfrac{\text{degrees}}{\text{cm.}} \times \text{sec.}}$$

In obtaining these results it was assumed that the readings of the four thermometers indicated correctly the temperatures of their bulbs. But this assumption is seldom valid in the case of thermometers such as those used by students. The error due to this imperfection has the greatest influence in the case of the thermometers *C* and *D*, since $\theta_3 - \theta_4$ is much less than $\theta_1 - \theta_2$. An approximate method of obtaining the corrections to be applied to $\theta_1 - \theta_2$ and to $\theta_3 - \theta_4$ is to compare *A* and *B* in a bath whose temperature is roughly $\frac{1}{2}(\theta_1 + \theta_2)$ and to compare *C* and *D* at the temperature $\frac{1}{2}(\theta_3 + \theta_4)$. When this was done in the above experiment the results became

(*a*) $\theta_1 - \theta_2 = 36°.2$ C., $\theta_3 - \theta_4 = 10°.9$ C., $K = .914$
(*b*) $\theta_1 - \theta_2 = 38°.9$ C., $\theta_3 - \theta_4 = 4°.8$ C., $K = .888$

As the thermometers were only read by estimation to $\frac{1}{10}$ degree, the agreement between these two values of K is as close as could be expected.

149. Thermal Conductivity of Liquids.

***150. Mechanical Equivalent of Heat with Puluj's Apparatus.**[1] The Mechanical Equivalent of Heat is the amount of mechanical work, expressed in ergs, required to raise the temperature of one gram of water one degree centigrade.

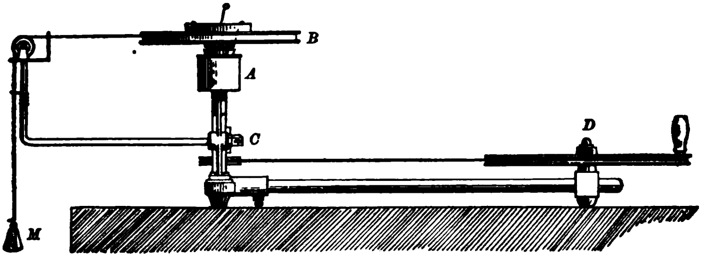

FIG. 3

1. *Description of the apparatus.* In the machine for this experiment, or " Jouler " as it may be called, shown in Fig. 3, a vertical spindle carries at its upper end a brass cup A. Into an ebonite ring concentric with A there fits tightly one of a pair of hollow truncated cones. The second cone fits into the first one and is provided with a pair of steel pins which correspond to the two holes in a grooved wooden disk B. In the experiment the disk B prevents the inner cone from revolving when the spindle and the outer cone revolve; it is the friction between the two cones which converts into heat the mechanical energy supplied. A cast-iron ring, resting on the disk and fixed by two pins, serves to give a suitable pressure between the cones.

A grooved pulley is fixed to the spindle, and by a string passing round this and also round a hand-wheel, D, motion is imparted to the spindle. There is a horizontal continuous revolution counter, C, actuated by a pair of bevel cog-wheels, to register the number of revolutions made by the vertical spindle.

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[1] The description of this apparatus is taken, by their kind permission, from that published by the makers W. G. Pye & Co., who adapted it from the manuscript notes prepared by Mr. G. F. C. Searle for use at the Cavendish Laboratory, Cambridge, England.

To the base of the apparatus one end of a bent steel rod is attached; the rod can be fixed in any position by a nut beneath the base. The other end of the rod carries a cradle in which runs a small guide pulley, this pulley being on the same level as the disk. The cradle turns freely about a vertical axis.

A fine string (*plaited* silk fishing line) is fastened to the disk and passes along the groove to its edge; it then passes over the pulley and is fastened to *M*, a mass of 200 or 300 grams. On turning the hand-wheel it is easy to regulate the speed so that the friction between the cones just causes *M* to be supported at a nearly constant level.

To prevent the string from running off the guide pulley, an eye is formed in the cradle in such a manner that the eye is on the same level as the groove of the pulley and about 5 cm. from the axle of the pulley towards the disk. If the string be passed through this eye it will always turn the cradle so that the string runs fairly over the pulley. In order to prevent the mass *M* from being wound up over the pulley, an eye is fixed to the steel rod and the string supporting *M* passes through this eye. With these arrangements it is impossible, even with unskilful driving of the hand-wheel, either to throw the string off the guide pulley or to wind *M* up over the pulley.

2. *Setting up the apparatus.* A thermometer is hung from a support so that it passes through the central aperture in the disk, and almost touches the bottom of the inner cone. The thermometer should also pass through the hole in the stirrer.

The string supporting *M* should be of such a length that, when as much as possible has been unwound from the disk, *M* is not quite in contact with the floor.

Before putting the cones together the rubbing surfaces must be carefully cleaned, and then four or five drops of oil must be put between them; the bearings of the spindle and guide pulleys should also be oiled.

3. *Method of Experimenting.* The cones, cleaned and oiled, are weighed together with the stirrer. The inner cone is then filled

up to about 1 cm. from its edge with water 2° or 3° below the temperature of the room, and the system is again weighed. The Jouler is now put into working order, one observer, X, taking his place at the hand-wheel, and a second observer, Y, at the Jouler. By working the Jouler the water is now warmed until its temperature is as nearly as possible equal to that of the room. After the counter has been read and the temperature (θ_1) of the water has been *carefully* observed and recorded, the operator X turns the hand-wheel fast enough to raise the mass M so far that the string supporting M is tangential to the edge of the disk. If the string be not tangential the moment of its tension about the axis of revolution is seriously diminished. The observer Y stirs the water and notes the temperature at each 100 revolutions of the spindle and gives a signal to X, who notes the time by aid of a watch. After Y has recorded the temperature upon a sheet of paper previously ruled for the purpose, he also records the time observed by X. *Very* accurate readings of these temperatures and times are difficult to make and are not necessary. It will be found that the time occupied by 100 revolutions of the spindle diminishes as the temperature rises; this effect is due to the diminution of the viscosity of the oil between the cones consequent upon the rise of temperature. When M is 200 grams the temperature will rise about 1° C. for each 100 revolutions of the spindle in the case of the Joulers supplied.

After about 1000 revolutions have been made by the spindle of the Jouler, the motion is stopped and the highest temperature (θ_2) shown by the thermometer is carefully read. The exact number of revolutions (n) made by the *spindle* is ascertained from the difference between the numbers registered by the counter at the start and finish.

Observations to determine the correction for cooling are then made. Without disturbing the apparatus, the temperature of the water is raised about 2° above θ_2 by working the Jouler. The Jouler is then brought to rest and the water is allowed to cool, with frequent stirring, and observations of the temperature are taken at intervals of about one minute till the water is only slightly (2 degrees or so) above the temperature of the room.

4. *Calculation of the correction for cooling.* If there had been no loss of heat during the time that the Jouler was in action, the

difference, $\theta_2 - \theta_1$, between the final and initial temperatures of the water could be used in the calculation without any correction. The correction necessary to allow for the loss of heat in the actual case is ascertained in the following manner: From the observations taken while the Jouler was in action a curve is plotted (the abscissa denoting time, and the ordinate temperature), showing how the temperature increased with the time. On account of the increase of speed due to the loss of viscosity of the oil the curve is concave upwards.

From the observations of the cooling of the water a second curve is drawn with time as abscissa and temperature as ordinate, and from it the rate of cooling in degrees per minute at any particular temperature is determined from the slope of the tangent to the curve. It is best not to actually *draw* the tangent. If a triangular "drawing square" *ABC* be adjusted so that one of its edges *AB* touches the curve at the desired point, and if one of the other sides, as *AC*, be made to slide along a straight edge, *AB* can be moved parallel to itself until it passes through an intersection of the lines ruled on the squared paper. It is now easy to read off along the edge of the square the number of degrees corresponding to 10 minutes. Dividing this number by 10, the rate of cooling in *degrees per minute* is obtained for the particular temperature at which the tangent was taken.

A third curve is now constructed. From the first curve the temperatures of the water at the end of 1, 2, 3... *minutes* are determined, and by the second curve the rates of cooling at these temperatures are determined. The third curve is drawn with the time as abscissa and the corresponding rate of cooling as ordinate. The origin is one point on the curve, since the water was initially at the temperature of the room. The area included between the line of times, the curve and the ordinate corresponding to the time when the Jouler was stopped, represents the correction to be added to $\theta_2 - \theta_1$, the observed rise of temperature. If 1 inch (or cm.) on the squared paper correspond to p minutes, and 1 inch (or cm.) correspond to q degrees per minute, then each square inch (or square cm.) represents pq degrees. If the area be A square inches (or square cm.) and ϕ be the correction to be added to $\theta_2 - \theta_1$, then $\phi = Apq$.

Since for small differences of temperature Newton's law of cooling is nearly true, and since the temperature of the water rises nearly uniformly, the correction, ϕ, to be added to $\theta_2 - \theta_1$, is approximately equal to half the product of the rate of cooling at the temperature θ_2 and the time occupied by the rise $\theta_2 - \theta_1$.

5. *Calculation of the work done.* When the spindle has made n turns, the work spent in overcoming the friction between the two cones is the same as would have been spent if the outer cone had been fixed and the inner one had been made to revolve by the descent of the mass M grams. In the latter case M would have fallen through $2\,\pi nr$ cm., where r centimeters is the radius of the groove of the wooden disk. Hence the total work spent in overcoming friction and thus producing heat is $2\,\pi nrMg$ ergs.

6. *Calculation of the heat produced.* Let W grams be the mass of the water, and w grams the mass of the cones and stirrer.

The specific heat of the metal may be taken as .095, and thus the system of cones, stirrer and water is thermally equivalent to $(W + .095\,w)$ grams of water.

If the thermometer have a large bulb it is necessary to take account of its water equivalent. The water equivalent is found by heating the thermometer and plunging it while hot into a small vessel of thin copper containing a known quantity of water at a known temperature. From the temperature of the thermometer at the instant when it is plunged into the water and from the rise of temperature of the water the water equivalent is calculated. Its value must be added to $W + .095\,w$ in the equation for J.

During the action of the Jouler the heat in the system of cones, stirrer and water has increased by $(\theta_2 - \theta_1)\,(W + .095\,w)$ units, while $\phi\,(W + .095\,w)$ units have escaped from that system by radiation, conduction and convection. Hence the total number of thermal units produced is $(W + .095\,w)\,(\theta_2 - \theta_1 + \phi)$ calories.

7. *Calculation of the Mechanical Equivalent of Heat.* If J denote the number of ergs of work which must be spent to raise the temperature of one gram of water by one degree we have

$$J = \frac{2\,\pi nrMg}{(W + .095\,w)\,(\theta_2 - \theta_1 + \phi)}\ \frac{\text{ergs}}{\text{calories}}$$

151. **Radiation of Heat.** (Ames and Bliss, Experiment LVI.)

152. **Heat of Solution.** (Whiting, paragraph 99.) Determine the Latent Heat of solution of Common Table Salt (Sodium Chloride) by the method described in the reference, using 10, 20, 30, 40, and 50 grams of salt respectively to 100 grams of water.

153. **Heat of Combination.** (Whiting, paragraphs 105, 106.)

154. **Heat of Combustion.** (Whiting, paragraph 107.)

*155. **Regnault's Hygrometer.** (Miller, § 151.) Determine the Relative Humidity of the air in the Laboratory with this instrument.

The relative humidity can be determined from the readings of the hygrometer by means of Tables 20 and 21 in Miller.

156. **Daniell's Hygrometer.** (Ganot, § 440.) Determine the Relative Humidity of the air in the Laboratory with this instrument.

The relative humidity can be obtained from the readings of the hygrometer by means of Tables 20 and 21 in Miller.

157. **United States Weather Bureau Psychrometer.** (Miller, pages 200–202.) Determine the Relative Humidity of the air in the Laboratory with this instrument.

Compare the result with a reading made either with the Regnault or the Daniell Hygrometer.

158. **The Variation of Solubility with the Temperature.** Determine the solubility of some salt for different temperatures, and plot the results.

*159. **The Phenomenon of Surfusion.** Under certain conditions, a liquid may be cooled below its freezing point without solidifying. To do this, it must be free from dust particles and air bubbles, and kept very still. If, when in this state, solid particles are dropped into it, or it is shaken, it is likely to solidify instantaneously. Water has been cooled in this manner to − 20° C. before freezing.

Determine how low you can make the temperature of water fall before it freezes.

Make a freezing mixture of about two-thirds broken ice and one-third table salt. In this, place a test tube containing distilled water which has been previously boiled for some time and then filtered. In the test tube, suspend a thermometer reading to about −20° C., so that the bulb of the thermometer is covered by the water. The temperature of the water in the test tube will fall rapidly, and will probably go below zero degrees centigrade before the water freezes. *You can tell when the water freezes by a sudden rise in the reading of the thermometer.* Record the thermometer readings every 30 seconds as the temperature falls. Make at least five independent sets of observations. The more carefully the experiment is performed, the greater will be the depression of the freezing point.

LIGHT

160. **Angle of a Prism with the Gaussian Eye-piece Spectrometer.** (Ames and Bliss, Experiment LXXXVII, Method 1.)

161. **Angle of a Prism with the Fixed Table Spectrometer.** (Ames and Bliss, Experiment LXXXVII, Method 2.)

162. **Angle of a Prism with the Movable Table Spectrometer.** (Ames and Bliss, Experiment LXXXVII, Method 3.)

163. **Angles of a Crystal with the Wollaston Goniometer.** (Miller, Experiment CV, § 170.)

*164. **Angles with the Sextant.** (Miller, Experiment XII, § 37.) Measure with this instrument the angle between two of the towers or two of the buildings seen from the Laboratory. Any two may be chosen, but you should state in your notes which two you used. Be careful to determine the index correction, and to apply it to your readings.

165. **The Measurement of Small Distances with the Optical Micrometer.** (Miller, Experiment IX, §§ 31–33.

166. **Index of Refraction with the Spectrometer by the Method of Minimum Deviation.** (Ames and Bliss, Experiments LXXXVIII and LXXXIX.)

167. **Index of Refraction by the Method of Total Reflection with the Spectrometer.** (Kohlrausch, § 40, Part IV.)

168. **Index of Refraction by Displacement.** (Miller, Experiment CX, § 181.)

169. **Index of Refraction with a Microscope.** (Miller, Experiment CIX, § 180.)

*170. **Index of Refraction with the Abbe Refractometer.** (Kohlrausch, § 40, Part III.) 1. Measure with this instrument the Index of Refraction, for *sodium light*, of water, alcohol, and of some of the aromatic oils.

2. Repeat the measurements with *white light*, using the compensator and compare the results obtained in the two cases.

The temperatures at which the measurements are made should be recorded.

After the experiment is finished, carefully clean the glass prisms of the instrument with a soft clean linen cloth.

*171. **Index of Refraction of a Liquid with a Lens.** Place some of the liquid between a double convex lens and a piece of plate glass. The liquid then forms a plano-concave lens, the curvature of which is equal to, but of opposite sign to that of the face of the convex lens which it touches.

The theory of optics shows that the principal focus of the combination of the two lenses is given by the formula

$$\frac{1}{F} = \frac{1}{f} - \frac{1}{f'}$$

where F is the principal focus of the combination; f, the principal focus of the double convex lens; and f', the principal focus of the concave lens.

From this formula we obtain directly

$$f' = \frac{fF}{F - f}$$

f and F can be found experimentally by the Method of Conjugate Foci described in Experiment 174.

Having determined f and F by experiment, and from their values calculated f' the principal focus of the plano-concave liquid lens, we can, if we know its radius of curvature, compute the index of refraction of the liquid which forms it. For a plano-concave lens having a principal focus f', a radius of curvature r, and an index of refraction n, we have the formula

$$\frac{1}{f'} = (n - 1)\frac{1}{r}$$

From which we obtain

$$n = \frac{r}{f'} + 1$$

r is equal to the radius of curvature of the surface of the convex lens touching the liquid, but with the opposite sign, since the surface of the liquid being concave r is negative. It can be determined either with the Spherometer (Experiment 5) or by the Method of Reflection (Experiment 342).

Determine, by this method, the Index of Refraction of water.

172. **Index of Refraction with the Michelson Interferometer.** (Mann, Chapter V, Experiment III.) Before beginning the experiment, read pages 48–55 in the reference.

*173. **Index of Refraction with Kohlrausch's Total Reflectometer.** (Miller, § 183.)

*174. **Principal Focus of a Convex Lens by the Method of Conjugate Foci.** The object of this experiment is to determine the principal focal distance of a convex lens.

If a convex lens is placed at a distance p from a source of light, an image of this source will be formed at a distance q on the other side of the lens. The theory of optics shows that

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}$$

where f is constant for a given lens, and is called its principal focal distance, because it is the distance from the lens at which parallel rays entering it are focused. Corresponding values of p and q are called conjugate focal distances, and the points themselves at which the object and image exist are called conjugate foci.

To perform the experiment, place the lens at any convenient distance p from the bright source of light which serves as an object, and move the screen on the other side of the lens to and fro until a position is found in which a sharp image of the object is formed upon it. This distance of the screen from the lens is q, and p and q are conjugate focal distances. Having determined p and q for this case, change the distance p and find the corresponding value of q. Find, in this manner, five pairs of values of p and q, and compute f for each case. The mean of these five values of f will give the principal focal distance of the lens.

175. **Principal Focus of a Concave Lens by the Shadow Method.** (Sabine, First Edition, Experiment XLI.)

*176. **Principal Focus of a Concave Lens by combining it with a Convex Lens, so that the Lenses touch Each Other.** Since the focus of a concave lens is virtual, it cannot be determined directly. It can, however, be found by combining the concave with a more powerful convex lens.

Fasten the two lenses together with a rubber band, and determine the principal focus of the combination by the method of Conjugate Foci (Experiment CLXXIV). Having done this, determine by the same method the principal focus of the convex lens by itself. In each case make five pairs of readings.

Knowing the principal focal distance F of the combination, and also F of the convex lens, you can calculate the principal focal distance of the concave lens F_2 from the formula

$$\frac{1}{F_2} = \frac{1}{F} - \frac{1}{F_1}$$

or

$$F_2 = \frac{F_1 F}{F_1 - F}$$

*177. **Principal Focus of a Concave Lens by combining it with a Convex Lens, the Lenses not touching Each Other.** (Miller, § 166.) Make five pairs of readings. Calculate the principal focal distance for each pair, and take the mean of these values.

178. **Magnifying Power of a Convex Lens.** (Sabine, First Edition, Experiment XL.) Take five pairs of read-

ings and plot a curve showing the relation of the magnifying power to the distance of the lens from the object.

*179. **Magnifying Power of a Telescope.** (Glazebrook and Shaw, § 56.) Make five observations of the magnifying power with the scale at different distances from the telescope. Begin with the scale about three meters away from the telescope, and then move it in about fifty centimeters at a time.

Plot a curve with the results showing the relation of the magnifying power to the distance.

180. **Construction of a Microscope.** (Ames and Bliss, Experiment LXXXVI.)

*181. **Use of the Microscope.** (Watson, Text-Book, § 357.) A box of microscopical preparations will be given to the student. Each slide has mounted upon it some object suitable for observation under the microscope. Carefully observe each object, using different objectives and eye-pieces to change the magnification. Make careful drawings in your note-book of the magnified images of at least two of these objects.

*182. **Magnifying Power of a Microscope.** (Miller, § 169, page 222.) Make a determination of the magnifying power of a microscope, using at least two objectives of differing powers and two eye-pieces.

183. **Angular Aperture of a Microscope.** (Kohlrausch, § 45, III, (3).)

184. **Radius of Curvature of a Mirror with the Spherometer.** (Sabine, page 7.)

*185. **Radius of Curvature of a Convex Mirror by Reflection.** A strip of paper with square ends is pasted on the mirror near its middle. At a suitable distance from the mirror is placed a screen with a scale, carrying riders, in front of it. The paper strip on the mirror and the image of the scale are observed through a hole in the screen just above the scale. The mirror should be so placed that its axis passes through the hole in the screen.

The paper strip, as seen through the hole in the screen, will appear to cover a certain number of divisions on the image of the scale. Move the riders on the scale until their inner edges appear to coincide with the edges of the strip of paper.

In Fig. 4, let *ab* be the strip of paper on the mirror; *A* and *B* the points on the scale which appear to coincide with the ends of the strip of paper; *E*, the hole in the screen; and *C*, the center of curvatuer of the mirror.

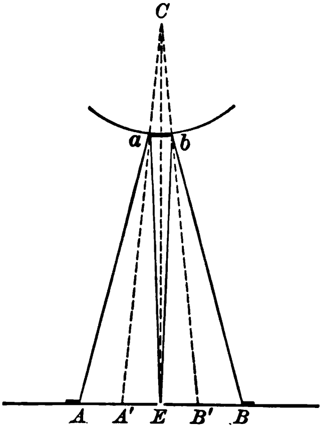

FIG. 4

Call *ab*, l; AB, L; the radius of the mirror, *Ca* or *Cb*, R; and its distance from the scale, d. Then, if l is small compared with d, since the angle of reflection is equal to the angle of incidence, and the triangles *Cab* and $CA'B'$ are similar, we have

$$\frac{R}{l} = \frac{R + d}{\frac{1}{2}L}$$

or

$$R = \frac{2\,dl}{L - 2l}$$

Measure l, L, and d and make five independent determinations of the radius of curvature of a convex mirror by this method. Take the mean value for the result. l being the smallest quantity involved must be measured the most carefully.

*186. **Radius of Curvature of a Concave Mirror by the Method of Conjugate Foci.** If p is the distance of an object from a Concave Spherical Mirror, measured along its axis, and q is the distance of the image, theory shows that the radius of curvature, R, of the mirror is given by the formula

$$\frac{1}{p}+\frac{1}{q}=\frac{2}{R}$$

And also, that its principal focal distance, f, that is, the distance from it at which parallel rays are focused, is given by

$$f=\frac{R}{2}$$

To determine the radius of curvature of a concave mirror, therefore, we produce, with the mirror, the image of some bright object upon a screen, and measure the distance of the object and the image from the mirror. These quantities give p and q. From them we can calculate R.

Determine, in this way, five pairs of values of p and q. Calculate R in each case. Take the mean of these values for R.

187. **Radius of Curvature of a Mirror of Slight Curvature by the Method of the Virtual Focus.** (Kohlrausch, § 43, III.)

188. **Radius of Curvature of a Convex Mirror by combining it with a Concave Mirror.** (Miller, § 163.)

*189. **Spectrum Analysis with a Flame Spectrum.** (Miller, § 201.) 1. Determine the characteristic lines of Sodium, Barium, Strontium, Lithium, Calcium, and Potassium. Make diagrams in your note-book showing the positions of these lines in the spectrum for each of these elements.

2. Having mapped the lines for each of these elements, determine the composition of three unknown mixtures of them made up by the Instructor.

Before using the spectroscope, two important adjustments should be made.

i. Adjust the observing telescope for parallel rays by focusing it on a distant object, such as a church spire.

ii. Keeping the observing telescope adjusted for parallel rays, move the slit of the collimating telescope in and out, until its image, as seen through the observing telescope, is clear and distinct.

190. **Spectrum Analysis with a Spark Spectrum.** (Sabine, First Edition, Experiment XLV.)

191. **Spectrum Analysis with an Absorption Spectrum.** (Sabine, First Edition, Experiment XLVI.)

192. **The Solar Spectrum.** (Miller, §§ 201, 202.)

193. **Dispersion Curve of a Prism with the Bunsen Spectroscope.** (Miller, § 201.) Determine the scale readings of the instrument for the spectral lines of Potassium, Lithium, Sodium, and Strontium. Look for the wave lengths of these lines in Kohlrausch's table, and then plot a curve in which ordinates represent wave lengths and abscissas scale readings. Then from this dispersion curve determine the wave lengths of several of the Barium and Calcium lines.

*194. **Spectrum Analysis with the Direct Vision Spectroscope.** (Sabine, Experiment XVI.)

*195. **Photometry with the Bunsen Photometer.** (Watson, Text-Book, §§ 361–364.) Determine the candle power of an incandescent electric lamp with the Bunsen Photometer by comparing it with a *standard candle.* This candle is made of spermaceti wax and is supposed to burn 7.776 grams per hour. To correct for possible variations in the amount of wax burned per hour, due to air currents and other causes, weigh the candle at the beginning and at the end of the experiment, note the time during which it burns, and determine the amount of wax burned per hour. For small variations from the standard amount the intensity of its light may be taken as proportional to the amount of wax burned per hour. If it burns 7.776 grams an hour the intensity of the standard candle will be unity. If it burns more or less than this per hour, a correction must be made for its intensity proportional to its rate of burning.

Determine the candle power of the incandescent lamp in its three principal positions, namely with the filament face on, edge on and end on. Take three pairs of readings for each position. Find the corrected value for the intensity of the standard candle and calculate the candle power for each pair of readings, and take the mean of the nine values thus obtained for the mean candle power of the electric lamp.

*196. **Photometry with the Rumford Photometer.** (Whiting, Experiment XL, II.)

197. **Photometry with the Lummer-Brodhun Photometer.** (Miller, § 159.)

198. **Wave Length by Interference, using Newton's Rings.** (Sabine, § 14.)

*199. **Wave Length by Interference, using Michelson's Interferometer.** (Mann, Chapter V, Experiment I.) Read the theory of this instrument on pages 48–55 of the reference, and perform Experiment I.

200. **Ratio of the Wave Lengths of Sodium Light with the Michelson Interferometer.** (Mann, Chapter V, Experiment II.) Read the theory of this instrument on pages 48–55 of the reference, and perform Experiment II.

*201. **Wave Length with the Transmission Grating; the Incident Light being Normal to the Grating.** (Watson, Text-Book, § 377, and Sabine, § 15.) Before beginning the experiment, read the theory of it in Watson, Text-Book, § 377.

202. **Wave Length with a Transmission Grating by the Method of Minimum Deviation.** (Miller, § 189, last paragraph.)

203. **Wave Length with a Reflection Grating.** (Miller, § 189.)

*204. **The Phenomenon of the Polarization of Light.** (Barker, §§ 448–457.) Examine reflected and refracted light with a Nicol's prism, and record the results of your observations. Also record the behavior of light passing through a pair of Tourmaline Tongs as one of the Tourmaline crystals is rotated.

What is meant by the polarization of light? How can it be achieved? And how observed? In how many different ways can light be polarized?

205. **Babinet's Compensator.** (Mann, § XIII.)

*206. **Norremberg's Polariscope.** (Ganot, §§ 682–692.) Observe, and record with drawings, the appearance of sections of a number of crystals, (1) when the upper mirror is parallel to the lower one, and (2) when rotated through 90°. Do this both for parallel light and for convergent light.

*207. **Specific Rotation with Laurent's Polarimeter.** (Miller, §§ 203–205.) Determine the Specific Rotation of

Cane Sugar, using solutions of 5, 10, 15, 20, and 25 grams of sugar to 100 grams of solution, respectively.

*208. **Specific Rotation with Wilds' Polarimeter.** (Miller, § 203 and § 204, Interference Bands (Wild). Determine the Specific Rotation of Cane Sugar, using solutions of 5, 10, 15, 20, and 25 grams of sugar to 100 grams of solution, respectively.

*209. **Color Analysis with Maxwell's Disks.** (Ames and Bliss, Experiment XC.) 1. Try any combination of normal colors, mixing them by rotation of the disks. Match the resultant color with one of the colors in the small book of colors supplied to the student. Try several combinations.

2. To each of the normal colors add portions of white light by using part of a white disk; observe the effect as more and more of the white disk is used.

3. Do the same thing with a black disk.

4. Find several pairs of complementary colors by combining certain of the normal colors in such proportions that they form a neutral gray. *This differs from white only in illumination.* The different colors should be so combined that the circle is divided in two equal parts, one of which is occupied by the color whose complement is to be found. The two halves of the circle should give equal illuminations. This can be adjusted by the use of white or black disks. Suppose, for instance, that the following colors, combined in the given proportions, make a gray:

Normal red . . .	.4
Normal blue . . .	.1
Normal green . . .	.45
White	.05

We then find the resultant of the green and white by combining them alone, and match it. The resultant of red and blue is found in the same way. These two resultant colors are complementary. Record your results by constructing miniature disks representing the colors actually used, and pasting them in the note-book. The resultant colors which are complementary to each other can be given either by pieces of the colored papers which match them, or by their names taken from the small book of colors.

210. **Color Analysis with the Color Box.** (Watson, § 400.)

211. **Color Analysis with the Spectroscope.**

212. **Selective Absorption of Light with the Spectroscope.** (Watson, § 386.)

213. **Anomalous Dispersion.** (Watson, Text-Book, § 389.) Observe the spectrum of white light, first with a solid glass prism, and then with a hollow glass prism filled with a solution of Fuchsine in alcohol. Record the results, making a drawing of the spectrum in each case.

ELECTRICITY AND MAGNETISM

*214. **Magnetic Field of Force with Iron Filings.** (Watson, Text-Book, § 421.) Examine and draw in the note-book: (1) Field of Force of one magnet by itself; (2) of two magnets, placed end to end, with their *unlike* poles opposite to each other; (3) of two magnets, placed end to end, with their *like* poles opposite to each other; (4) of two magnets, side by side, unlike poles opposite; (5) of two magnets, side by side, like poles opposite; and (6) Field of Force of the end of one of the magnets in a plane at right angles to its axis.

*215. **Magnetic Field of Force with a Magnetic Table.** (Stratton and Millikan, Experiment XL, *a*.) Plot the

Field of Force (1) for a single pole, (2) for two unlike poles, and (3) for two like poles. Make copies of these diagrams in your note-book on a reduced scale.

216. **Magnetic Field of Force with a Compass.** (Ames and Bliss, Experiment LXIII.)

217. **Comparison of Magnetic Fields by the Method of Vibrations.** (Ames and Bliss, Experiment LXV.)

218. **Strength of a Magnetic Field with an Earth Inductor.** (Stewart and Gee, Volume II, Lesson LXXI.)

219. **Comparison of Magnetic Fields with the Bismuth Spiral.**

*220. **Distribution of Magnetism in a Magnet by the Method of Vibrations.** (Sabine, First Edition, Experiment XLIX.)

221. **Distribution of Magnetism by the Test Nail Method.** (Stewart and Gee, Volume II, Lesson XIII.)

222. **Distribution of Magnetism with the Ballistic Galvanometer.** (Stewart and Gee, Volume II, Lesson LXXII.)

223. **Temperature Coefficient of a Magnet.** (Kohlrausch, § 62 A.)

224. **Permeability with the Magnetometer.** (Henderson, §§ 294–301.)

225. **Permeability with the Ballistic Galvanometer.** (Henderson, §§ 302–311.)

226. **Determination of the Magnetism in a Bar in Absolute Measure.** (Kohlrausch, § 62.)

*227. **Determination of H with the Magnetic Pendulum and the Magnetometer.** (Sabine, pages 60–63.)

228. **Determination of H with the Tangent Galvanometer and the Copper Voltameter.** (Ames and Bliss, Experiment LXXVI.)

229. **Determination of H with the Tangent Galvanometer and the Water Voltameter.** (Ames and Bliss, Experiment LXXV.) Instead of determining the Galvanometer Constant *G*, compute this quantity from the number of turns and mean diameter of its coil, and determine *H*.

230. **Magnetic Dip with the Dip Circle.** (Ames and Bliss, Experiment LXIV.)

*231. **Magnetic Dip with the Earth Inductor.** (Ames and Bliss, Experiment LXXVIII.)

*232. **Measurement of Current with the Tangent Galvanometer.** (Sabine, pages 64–67.)

233. **Measurement of Current with the Helmholtz Tangent Galvanometer.** (Henderson, §§ 142, 143.)

234. **Measurement of Current with the Sine Galvanometer.** (Henderson, §§ 144, 145.)

*235. **Equipotential Lines and Lines of Flow.** (Sabine, page 73.)

236. **Magnetic Field of Force due to a Circular Current.** (Stewart and Gee, Volume II, Lesson LVI.)

237. **Figure of Merit of a Galvanometer.** (Stewart and Gee, Volume II, Lesson XVIII.)

*238. **Resistance with a Wheatstone Bridge of the Slide Wire Form.** (Sabine, pages 74, 75.) Measure with this instrument the resistances of three coils of wire. Having measured the resistance of each coil separately, measure the resistance of two in series, of three in series, of two in parallel and of three in parallel. Do your results confirm the laws for the resistance of conductors connected in series, and in parallel? For a statement of these laws see Hastings and Beach, § 390.

*239. **Resistance with a Wheatstone Bridge of the Box Form (Post-office Box).** (Sabine, pages 76, 77.) Measure with this instrument the resistances of three coils of wire. Having measured the resistance of each coil separately, measure the resistance of two in series, of three in series, of two in parallel and of three in parallel. Do your results confirm the laws for the resistance of conductors connected in series, and in parallel? For a statement of these laws see Hastings and Beach, § 390.

240. **Resistance of a Galvanometer by Thomson's Method.** (Stewart and Gee, Volume II, Lesson XXV.)

241. **Resistance with a Tangent Galvanometer.** (Miller, § 217.)

*242. **Resistance of a Voltaic Cell by Ohm's Method.** (Stewart and Gee, Volume II, Lesson XXXIX.)

243. **Resistance of a Voltaic Cell by Thomson's Method.** (Stewart and Gee, Volume II, Lesson XXXV.)

*244. **Resistance of a Voltaic Cell by Mance's Method.** (Miller, § 228.) When the current flows through the galvanometer, the deflection of the needle will be so great that it cannot be read on the scale. To overcome this the needle may be controlled by a large magnet placed near the galvanometer. This control magnet should be placed in such a position that the galvanometer needle lies in the plane of the coil, since the galvanometer is most sensitive when the needle is in this position.

245. **Resistance of a Voltaic Cell by Beetz's Method.** (Stewart and Gee, Volume II, Lesson XXXVIII.)

246. **Resistance of a Voltaic Cell by the Condenser Method.** (Henderson, §§ 86–88.)

247. **Temperature Coefficient of a Voltaic Cell.** (Henderson, § 196.)

248. **Low Resistance with the Kelvin Double Bridge.** (Watson, Practical Physics, § 191.)

249. **High Resistance with a Galvanometer.** (Stewart and Gee, Volume II, Lesson XXXIII.)

250. **High Resistance with an Electrometer.** (Henderson, § 73.)

*251. **Specific Resistance of Metals.** The specific Resistance, or Resistivity, of a substance is the resistance between opposite faces of a cube of the substance one centimeter on a side. Experiment shows that the resistance, R, of a wire, l cm. long, having a cross-section of A square cm., and made of a substance whose specific resistance is S, is given by

$$R = S\frac{l}{A}$$

Therefore

$$S = \frac{RA}{l}$$

Measure the resistance, length, and diameter of a wire, and calculate the specific resistance of the metal of which it is made. Its resistance can be measured with a Wheatstone Bridge, and its diameter with a micrometer caliper.

Observe and record the temperature at which the measurement is made. This is important, since the resistance varies with temperature.

*252. **Temperature Coefficient of Resistance.** The Temperature Coefficient of Resistance of a substance is its change in resistance per *ohm* per degree. If its resistance changes from R_1 to R_2, when its temperature changes from t_1 to t_2, its temperature coefficient, K, is given by

$$K = \frac{R_2 - R_1}{R_1 (t_2 - t_1.)}$$

A spool of wire is placed in a bath of kerosene oil, surrounded by a water bath. A thermometer is placed in the oil. Both baths are stirred until the temperature of the thermometer becomes constant. The resistance of the coil is then measured. The water is heated until the temperature of the oil is about 50° C., and the resistance of the coil again measured. From these resistances and their corresponding temperatures, the coefficient can be calculated.

253. **Specific Resistance of Solutions by Horsford's Method**. (Stewart and Gee, Volume II, Lesson XXXV, Horsford's Method.)

*254. **Specific Resistance of Solutions by Kohlrausch's Method**. (Miller, Lesson CXXXII, §§ 231, 232.) Determine the Specific Resistance, in the manner described in the reference, of 1, 5, 10, 15, and 20 per cent. solutions of Copper Sulphate.

With the results, plot a curve showing the variation of Specific Resistance with concentration. Take concentrations for abscissas and Specific Resistances for ordinates.

255. **Specific Resistance of Solutions by Mance's Method using the Electrodynamometer.** (Stewart and Gee, Volume II, § 80.)

*256. **Absolute Measurement of Resistance with the Calorimeter**. (Sabine, pages 77–79.)

257. **Absolute Measurement of Resistance with the Earth Inductor**. (Kohlrausch, Experiment LXXXII, II.)

*258. **Electromotive Force of a Voltaic Cell by Ohm's Method**. (Sabine, page 80.) The values of the current must be calculated from the readings of the Tangent Galvanometer as explained in Experiment LIII, Sabine. If the value of *H* for that part of the laboratory in which the experiment is made has not previously been determined by the student, he may obtain its value from the Instructor.

259. **Electromotive Force of a Voltaic Cell by Wiedemann's Method.** (Sabine, First Edition, Experiment LXVI.)

260. **Electromotive Force of a Voltaic Cell by the High Resistance Method.** (Ames and Bliss, Experiment LXXIII.)

261. **Electromotive Force of a Voltaic Cell with a Ballistic Galvanometer and a Condenser.** (Ames and Bliss, Experiment LXXIV.)

*262. **Electromotive Force of a Voltaic Cell with a Potentiometer.** (Sabine, Experiment XXIV, page 79.)

263. **Electromotive Force of a Voltaic Cell with a Quadrant Electrometer.** (Miller, Experiment CXLIII, § 254.)

264. **Construction of a Paraffin Paper Condenser.** (Stewart and Gee, Volume II, Appendix F, § 6.)

*265. **Capacity of a Condenser with a Ballistic Galvanometer.** (Miller, Experiment CXLVIII, §§ 262–264.) Determine by this method the capacity of a condenser, by comparing it with a standard.

266. **Capacity of a Condenser by the Electrometer Method.** (Henderson, § 250.)

267. **Capacity of a Condenser by the Method of Mixtures.** (Stewart and Gee, Volume II, Lesson LXXX.)

268. **Capacity of a Condenser by the Bridge Method using a Direct Current.** (Stewart and Gee, Volume II, Lesson LXXIX.)

269. **Capacity of a Condenser by the Bridge Method using an Alternating Current.** This experiment is to be conducted in the manner of the preceding experiment, except that a telephone takes the place of the galvanometer, and a source of alternating current the place of the battery.

The balancing resistances should be non-inductive, and the wires leading to the condenser as short as possible. The variable resistance must be adjusted until the sound in the telephone is reduced to a minimum.

270. **The Dielectric Constant for Solids.** (Henderson, § 254.) The Dielectric Constant, formerly known as the Specific Inductive Capacity, is now generally known as the Permittivity.

271. **The Dielectric Constant for Liquids.** (Henderson, § 264.)

272. **Self Inductance by Rayleigh's Method.** (Stewart and Gee, Volume II, Lesson LXXIII.)

273. **Self Inductance by Maxwell's Method.** (Henderson, § 327.)

274. **Relative Measurement of Self Inductance with the Galvanometer.** (Stewart and Gee, Volume II, Lesson LXXIV.)

275. **Relative Measurement of Self Inductance with an Alternating Current and a Telephone.** This experiment is to be performed in the manner of the preceding, except that a telephone takes the place of the galvanometer, and a source of alternating current the place of the battery.

276. **Mutual Inductance of Two Coils.** (Stewart and Gee, Volume II, Lesson LXXV.)

277. **Intensity of an Alternating Current with the Absolute Electrodynamometer.** (Henderson, §§ 148, 149.)

278. **Intensity of an Alternating Current with the Current Balance.** (Henderson, §§ 151–157.)

279. **Intensity of an Alternating Current with the Sieman's Electrodynamometer.** (Henderson, §§ 174–177.)

280. **Intensity of an Alternating Current with a Hot Wire Ammeter.**

281. **Frequency of an Alternating Current with a Sonometer and Magnet.**

*282. **Frequency of an Alternating Current with a Kundt's Tube and a Telephone.**

283. **Frequency of an Alternating Current by the Method of Beats.**

284. **Thermoelectric Force.** (Sabine, pages 81, 82.)

*285. **Electrochemical Equivalent of Copper.** (Ames and Bliss, Experiment LXXVI.) Read the reference carefully, but instead of determining G or H, determine the value of the Electrochemical Equivalent of Copper. The current passing through the Voltameter may be calculated from the reading of the Galvanometer, and from the number of turns and mean diameter of its coil. (See Sabine, Experiment LIII). If the value of H for that part of the Laboratory in which the experiment is made has not previously been determined by the student, he may obtain its value from the Instructor. If a current i, flowing for a time t, deposits a mass m of copper, the Electrochemical Equivalent ϵ is given by the formula

$$\epsilon = \frac{m}{it}$$

*286. **Electrochemical Equivalent of Hydrogen.** (Ames and Bliss, Experiment LXXV.) Read the reference carefully, but instead of determining the galvanometer constant determine the value of the Electrochemical Equivalent of Hydrogen. The instructions for the preceding experiment (No. 496) hold for this, if " hydrogen " is substituted for " copper."

***287. The Mechanical Equivalent of Heat by the Heating Effect of a Current.** (Ames and Bliss, Experiment LXXVII.) Set up the apparatus as instructed in the reference, omitting, however, the Voltameter, as the current can be measured with sufficient accuracy by the Tangent Galvanometer. If the value of H for that part of the laboratory in which the experiment is made has not previously been determined by the student, he may obtain its value from the Instructor.

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